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(71) Applicant *(for all designated States except US)*: **QUALCOMM INCORPORATED** [US/US]; 5775 Morehouse Drive, San Diego, California 92121 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **KADOUS, Tamer** [EG/US]; 11116 Ivy Hill Drive, San Diego, California 92131 (US). **KHANDEKAR, Aamod** [IN/US]; 8465 Regents Road, #339, San Diego, California 92122 (US). **GORE, Dhananjay, Ashok** [IN/US]; 8465 Regents Road, #436, San Diego, California 92122 (US). **GOROKHOV, Alexei** [FR/US]; 12543 El Camino Real, San Diego, California 92130 (US).

(74) Agents: **OGROD, Gregory, D.** et al.; 5775 Morehouse Drive, San Diego, California 92121 (US).

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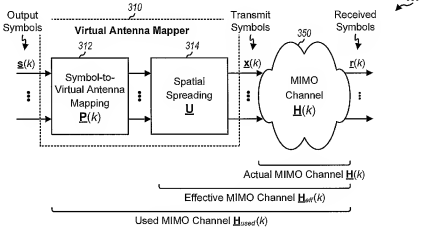
(54) **Title:** METHOD AND APPARATUS FOR PROVIDING ANTENNA DIVERSITY IN A WIRELESS COMMUNICATION SYSTEM



(57) **Abstract:** Transmission schemes that can flexibly achieve the desired spatial multiplexing order, spatial diversity order, and channel estimation overhead order are described. For data transmission, the assigned subcarriers and spatial multiplexing order (M) for a receiver are determined, where $M \geq 1$. For each assigned subcarrier, M virtual antennas are selected from among V virtual antennas formed with V columns of an orthonormal matrix, where $V \geq M$. V may be selected to achieve the desired spatial diversity order and channel estimation overhead order. Output symbols are mapped to the M virtual antennas selected for each assigned subcarrier by applying the orthonormal matrix. Pilot symbols are also mapped to the V virtual antennas. The mapped symbols are provided for transmission from T transmit antennas, where $T \geq V$. Transmission symbols are generated for the mapped symbols, e.g., based on OFDM or SC-FDMA. Different cyclic delays may be applied for the T transmit antennas to improve diversity.

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METHOD AND APPARATUS FOR PROVIDING ANTENNA DIVERSITY IN A WIRELESS COMMUNICATION SYSTEM

[0001] The present application claims priority to provisional U.S. Application Serial No. 60/710,408, entitled "Method and Apparatus for Antenna Diversity in Multi-input Multi-Output Communication Systems," filed August 22, 2005, and provisional U.S. Application Serial No. 60/711,144 entitled "Method and Apparatus for Antenna Diversity in Multi-input Multi-Output Communication Systems," filed August 24, 2005, both assigned to the assignee hereof and incorporated herein by reference. The present application is further related to commonly assigned U.S. Patent Application Serial No. to be determined, entitled "Adaptive Sectorization in Cellular Systems," filed on the same day herewith, and incorporated herein by reference.

BACKGROUND

I. Field

[0002] The present disclosure relates generally to communication, and more specifically to transmission schemes for wireless communication.

II. Background

[0003] In a wireless communication system, a transmitter (e.g., a base station or a terminal) may utilize multiple (T) transmit antennas for data transmission to a receiver equipped with one or more (R) receive antennas. The multiple transmit antennas may be used to increase system throughput by transmitting different data from these antennas and/or to improve reliability by transmitting data redundantly. For example, the transmitter may transmit a given symbol from all T transmit antennas, and the receiver may receive multiple versions of this symbol via the R receive antennas. These multiple versions of the transmitted symbol generally improve the receiver's ability to recover the symbol.

[0004] Transmission performance may be improved by exploiting the spatial dimension obtained with the multiple transmit antennas and, if present, the multiple receive antennas. A propagation path exists between each pair of transmit and receive

antennas. T·R different propagation paths are formed between the T transmit antennas and the R receive antennas. These propagation paths may experience different channel conditions (e.g., different fading, multipath, and interference effects) and may achieve different signal-to-noise-and-interference ratios (SNRs). The channel responses for the T·R propagation paths may vary from path to path and may further vary across frequency for a dispersive wireless channel and/or over time for a time-variant wireless channel.

[0005] A major drawback to using multiple transmit antennas for data transmission is that the channel response between each pair of transmit and receive antennas (or each propagation path) typically needs to be estimated in order to properly receive the data transmission. Estimation of the full channel response for all T·R transmit and receive antenna pairs may be undesirable for several reasons. First, a large amount of link resources may be consumed in order to transmit a pilot used for channel estimation, which in turn reduces the link resources available to transmit data. Second, channel estimation for all T·R transmit and receive antenna pairs increases processing overhead at the receiver.

[0006] There is therefore a need in the art for transmission schemes that can ameliorate the need to estimate the full channel response for all transmit and receive antenna pairs.

SUMMARY

[0007] Transmission schemes that can flexibly achieve the desired spatial multiplexing order, spatial diversity order, and channel estimation overhead order are described herein. The spatial multiplexing order determines the number of symbols to send simultaneously on one subcarrier in one symbol period, the spatial diversity order determines the amount of spatial diversity observed by the transmitted symbols, and the channel estimation overhead order determines the amount of pilot overhead.

[0008] In an embodiment, for a data transmission from a transmitter to a receiver, the subcarriers assigned to the receiver and the spatial multiplexing order (M) for the receiver are determined, where $M \geq 1$. For each assigned subcarrier, M virtual antennas are selected from among V virtual antennas formed with V columns of an orthonormal matrix, where $V \geq M$. V may be selected to achieve the desired spatial diversity order

and channel estimation overhead order. The M virtual antennas for each assigned subcarrier may be selected in various manners, as described below. Output symbols for the receiver are mapped to the M virtual antennas selected for each assigned subcarrier by applying the orthonormal matrix. Pilot symbols are also mapped to the V virtual antennas. The mapped output symbols and pilot symbols (or transmit symbols) are provided for transmission from T physical transmit antennas, where $T \geq V$. Transmission symbols (e.g., OFDM symbols or SC-FDMA symbols) are generated for each transmit antenna based on the transmit symbols for that transmit antenna. Different cyclic delays may be applied to the transmission symbols for the T transmit antennas.

[0009] Various aspects and embodiments of the invention are described in further detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The features and nature of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout.

[0011] FIG. 1 shows a wireless communication system.

[0012] FIGS. 2A and 2B show MISO and MIMO channels, respectively.

[0013] FIG. 3 shows a transmission scheme with virtual antennas.

[0014] FIG. 4 shows a transmission scheme with virtual antennas and cyclic delay diversity.

[0015] FIG. 5 shows a MIMO transmission by cycling through the virtual antennas.

[0016] FIGS. 6A, 6B and 6C show three exemplary subcarrier structures.

[0017] FIG. 7 shows an exemplary frequency hopping scheme.

[0018] FIG. 8 shows an exemplary pilot scheme for symbol rate hopping.

[0019] FIG. 9A through 9D show four exemplary pilot schemes for block hopping.

[0020] FIG. 10 shows a process for transmitting data and pilot to one or more receivers.

[0021] FIG. 11 shows an apparatus for transmitting data and pilot to one or more receivers.

[0022] FIG. 12 shows a block diagram of a base station and two terminals.

DETAILED DESCRIPTION

[0023] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs.

[0024] **FIG. 1** shows a wireless communication system 100 with multiple base stations 110 and multiple terminals 120. A base station is a station that communicates with the terminals. A base station may also be called, and may contain some or all of the functionality of, an access point, a Node B, and/or some other network entity. Each base station 110 provides communication coverage for a particular geographic area 102. The term "cell" can refer to a base station and/or its coverage area depending on the context in which the term is used. To improve system capacity, a base station coverage area may be partitioned into multiple smaller areas, e.g., three smaller areas 104a, 104b, and 104c. Each smaller area is served by a respective base transceiver subsystem (BTS). The term "sector" can refer to a BTS and/or its coverage area depending on the context in which the term is used. For a sectorized cell, the BTSs for all sectors of that cell are typically co-located within the base station for the cell. The transmission techniques described herein may be used for a system with sectorized cells as well as a system with un-sectorized cells. For example, the techniques may be used for the system described in the aforementioned U.S. Patent Application Serial No. **[Attorney Docket No. 05091]**. For simplicity, in the following description, the term "base station" is used generically for a BTS that serves a sector as well as a base station that serves a cell.

[0025] Terminals 120 are typically dispersed throughout the system, and each terminal may be fixed or mobile. A terminal may also be called, and may contain some or all of the functionality of, a mobile station, a user equipment, and/or some other device. A terminal may be a wireless device, a cellular phone, a personal digital assistant (PDA), a wireless modem card, and so on. Each terminal may communicate with zero, one, or multiple base stations on the downlink and uplink at any given moment. The downlink (or forward link) refers to the communication link from the base stations to the terminals, and the uplink (or reverse link) refers to the communication link from the terminals to the base stations.

[0026] For a centralized architecture, a system controller 130 couples to base stations 110 and provides coordination and control for these base stations. For a distributed architecture, the base stations may communicate with one another as needed.

[0027] The transmission techniques described herein may be used for various wireless communication systems such as an orthogonal frequency division multiple access (OFDMA) system, a single-carrier frequency division multiple access (SC-FDMA) system, a frequency division multiple access (FDMA) system, a code division multiple access (CDMA) system, a time division multiple access (TDMA) system, a spatial division multiple access (SDMA) system, and so on. An OFDMA system utilizes orthogonal frequency division multiplexing (OFDM), which is a multi-carrier modulation technique that partitions the overall system bandwidth into multiple (K) orthogonal subcarriers. These subcarriers may also be called tones, bins, and so on. With OFDM, each subcarrier is associated with a respective subcarrier that may be modulated with data. An SC-FDMA system may utilize interleaved FDMA (IFDMA) to transmit on subcarriers that are distributed across the system bandwidth, localized FDMA (LFDMA) to transmit on a block of adjacent subcarriers, or enhanced FDMA (EFDMA) to transmit on multiple blocks of adjacent subcarriers. In general, modulation symbols are sent in the frequency domain with OFDM and in the time domain with SC-FDMA.

[0028] An OFDM symbol may be generated for one transmit antenna in one symbol period as follows. N modulation symbols are mapped to N subcarriers used for transmission (or N assigned subcarriers) and zero symbols with signal value of zero are mapped to the remaining $K-N$ subcarriers. A K-point inverse fast Fourier transform (IFFT) or inverse discrete Fourier transform (IDFT) is performed on the K modulation symbols and zero symbols to obtain a sequence of K time-domain samples. The last Q samples of the sequence are copied to the start of the sequence to form an OFDM symbol that contains $K+Q$ samples. The Q copied samples are often called a cyclic prefix or a guard interval, and Q is the cyclic prefix length. The cyclic prefix is used to combat intersymbol interference (ISI) caused by frequency selective fading, which is a frequency response that varies across the system bandwidth.

[0029] An SC-FDMA symbol may be generated for one transmit antenna in one symbol period as follows. N modulation symbols to be sent on N assigned subcarriers

are transformed to the frequency domain with an N-point fast Fourier transform (FFT) or discrete Fourier transform (DFT) to obtain N frequency-domain symbols. These N frequency-domain symbols are mapped to the N assigned subcarriers, and zero symbols are mapped to the remaining $K-N$ subcarriers. A K-point IFFT or IDFT is then performed on the K frequency-domain symbols and zero symbols to obtain a sequence of K time-domain samples. The last Q samples of the sequence are copied to the start of the sequence to form an SC-FDMA symbol that contains $K+Q$ samples.

[0030] A transmission symbol may be an OFDM symbol or an SC-FDMA symbol. The $K+Q$ samples of a transmission symbol are transmitted in $K+Q$ sample/chip periods. A symbol period is the duration of one transmission symbol and is equal to $K+Q$ sample/chip periods.

[0031] The transmission techniques described herein may be used for the downlink as well as the uplink. For clarity, much of the following description is for downlink transmission from a base station (a transmitter) to one or more terminals (receivers). For each subcarrier, the base station may transmit to one terminal without SDMA or to multiple terminals with SDMA.

[0032] **FIG. 2A** shows a multiple-input single-output (MISO) channel formed by multiple (T) transmit antennas 112a through 112t at base station 110 and a single receive antenna 122x at a terminal 120x. The MISO channel may be characterized by a $1\times T$ channel response row vector $\underline{\mathbf{h}}(k)$ for each subcarrier k, which may be given as:

$$\underline{\mathbf{h}}(k) = [h_1(k) \;\; h_2(k) \;\; \ldots \;\; h_T(k)] \;, \qquad \text{Eq (1)}$$

where $h_i(k)$, for $i = 1, \ldots, T$, denotes the coupling or complex channel gain between transmit antenna i and the single receive antenna for subcarrier k.

[0033] **FIG. 2B** shows a multiple-input multiple-output (MIMO) channel formed by the T transmit antennas 112a through 112t at base station 110 and multiple (R) receive antennas 122a through 122r at a terminal 120y. The MIMO channel may be characterized by an $R\times T$ channel response matrix $\underline{\mathbf{H}}(k)$ for each subcarrier k, which may be given as:

$$\underline{\mathbf{H}}(k) = \begin{bmatrix} h_{1,1}(k) & h_{1,2}(k) & \cdots & h_{1,\mathrm{T}}(k) \\ h_{2,1}(k) & h_{2,2}(k) & \cdots & h_{2,\mathrm{T}}(k) \\ \vdots & \vdots & \ddots & \vdots \\ h_{\mathrm{R},1}(k) & h_{\mathrm{R},2}(k) & \cdots & h_{\mathrm{R},\mathrm{T}}(k) \end{bmatrix} = [\underline{\mathbf{h}}_1(k)\ \underline{\mathbf{h}}_2(k)\ \ldots\ \underline{\mathbf{h}}_{\mathrm{T}}(k)], \qquad \text{Eq (2)}$$

where $h_{j,i}(k)$, for $j = 1, \ldots, \mathrm{R}$ and $i = 1, \ldots, \mathrm{T}$, denotes the complex channel gain between transmit antenna i and receive antenna j for subcarrier k; and

$\underline{\mathbf{h}}_i(k)$ is an $\mathrm{R} \times 1$ channel response vector for transmit antenna i, which is the i-th column of $\underline{\mathbf{H}}(k)$.

[0034] The transmitter may transmit one or more output symbols from the T transmit antennas on each subcarrier in each symbol period. Each output symbol may be a modulation symbol for OFDM, a frequency-domain symbol for SC-FDMA, or some other complex value. The data transmission may be quantified by the following metrics:

- Spatial multiplexing order (M) – the number of output symbols transmitted via the T transmit antennas on one subcarrier in one symbol period;
- Spatial diversity order (D) – the amount of spatial diversity observed by the transmitted output symbols; and
- Channel estimation overhead order (C) – the number of virtual antennas to be estimated by a receiver for each receive antenna.

In general, $\mathrm{M} \le \min\{\mathrm{T}, \mathrm{R}\}$, $\mathrm{D} \le \mathrm{T}$, and $\mathrm{C} \le \mathrm{T}$. The spatial diversity refers to transmit diversity resulting from the use of multiple transmit antennas and does not include receive diversity resulting from the use of multiple receive antennas.

[0035] If the transmitter transmits output symbols directly from the T transmit antennas, then a receiver typically needs to estimate the full channel response for all T transmit antennas in order to recover the data transmission. The channel estimation overhead order is then $\mathrm{C} = \mathrm{T}$. In certain scenarios, it may be desirable to transmit fewer than T output symbols simultaneously, e.g., if the channel conditions are poor. A subset of the T transmit antennas may be used to transmit fewer than T output symbols. However, this is undesirable since the transmit powers available for the unused transmit antennas are not judiciously employed for transmission.

[0036] The transmission schemes described herein allow for flexible selection of the three metrics M, D and C in order to achieve good performance for data transmission in different conditions. For example, a larger spatial multiplexing order M may be selected for good channel conditions with high SNRs, and a smaller spatial multiplexing order may be selected for poor channel conditions with low SNRs. A lower channel estimation overhead order C may be selected, e.g., in scenarios where low throughput due to low SNRs does not justify a large channel estimation overhead.

[0037] The transmission schemes described herein can utilize all T transmit antennas for transmission, regardless of the number of output symbols being sent and regardless of which subcarriers are used for transmission. This capability allows the transmitter to utilize all of the transmit power available for the T transmit antennas, e.g. by utilizing the power amplifiers coupled to each of the antennas, for transmission, which generally improves performance. Employing fewer than T transmit antennas for transmission typically results in less than all of the available transmit power being used for the transmission, which would impact performance.

[0038] The transmission schemes described herein can readily support MIMO, single-input multiple-output (SIMO), and single-input single-output (SISO) transmissions. A MIMO transmission is a transmission of multiple output symbols from multiple virtual antennas to multiple receive antennas on one subcarrier in one symbol period. A SIMO transmission is a transmission of a single output symbol from one virtual antenna to multiple receive antennas on one subcarrier in one symbol period. A SISO transmission is a transmission of a single output symbol from one virtual antenna to one receive antenna on one subcarrier in one symbol period. The transmitter may also send a combination of MIMO, SIMO and/or SISO transmissions to one or more receivers in one symbol period.

[0039] The transmitter may transmit M output symbols simultaneously from the T transmit antennas on one subcarrier in one symbol period using various transmission schemes. In an embodiment, the transmitter processes the output symbols for transmission, as follows:

$$\underline{\mathbf{x}}(k) = \underline{\mathbf{U}} \cdot \underline{\mathbf{P}}(k) \cdot \underline{\mathbf{s}}(k) \ , \qquad \text{Eq (3)}$$

where $\underline{\mathbf{s}}(k)$ is an $M \times 1$ vector containing M output symbols to be sent on subcarrier k in one symbol period;

$\underline{\mathbf{P}}(k)$ is a $V \times M$ permutation matrix for subcarrier k;

$\underline{\mathbf{U}} = [\underline{\mathbf{u}}_1 \ \underline{\mathbf{u}}_2 \ \ldots \ \underline{\mathbf{u}}_V]$ is a $T \times V$ orthonormal matrix; and

$\underline{\mathbf{x}}(k)$ is a $T \times 1$ vector containing T transmit symbols to be sent from the T transmit antennas on subcarrier k in one symbol period.

V is the number of virtual antennas formed with the orthonormal matrix $\underline{\mathbf{U}}$. In general, $1 \le M \le V \le T$. V may be a fixed value or a configurable value.

[0040] The orthonormal matrix $\underline{\mathbf{U}}$ is characterized by the property $\underline{\mathbf{U}}^H \cdot \underline{\mathbf{U}} = \underline{\mathbf{I}}$, where "^{H}" denotes a conjugate transpose and $\underline{\mathbf{I}}$ is the identity matrix. The V columns of $\underline{\mathbf{U}}$ are orthogonal to one another, and each column has unit power. In an embodiment, $\underline{\mathbf{U}}$ is defined such that the sum of the squared magnitude of the V entries in each row is equal to a constant value. This property results in equal transmit power being used for all T transmit antennas. $\underline{\mathbf{U}}$ may also be a unitary matrix that is characterized by the property $\underline{\mathbf{U}}^H \cdot \underline{\mathbf{U}} = \underline{\mathbf{U}} \cdot \underline{\mathbf{U}}^H = \underline{\mathbf{I}}$. Orthonormal and unitary matrices may be formed as described below. The V columns of $\underline{\mathbf{U}}$ are used to form V virtual antennas that may be used to send up to V output symbols on one subcarrier in one symbol period. The virtual antennas may also be called effective antennas or by some other terminology.

[0041] In an embodiment, a single orthonormal matrix $\underline{\mathbf{U}}$ is used for all K total subcarriers in all symbol periods, so that $\underline{\mathbf{U}}$ is not a function of subcarrier index k or symbol index n. In another embodiment, different orthonormal matrices are used for different subcarrier sets that may be assigned to different receivers. In yet another embodiment, different orthonormal matrices are used for different subcarriers. In yet another embodiment, different orthonormal matrices are used for different time intervals, where each time interval may span one or multiple symbol periods. In yet another embodiment, one or more orthonormal matrices are selected for use from among multiple orthonormal matrices, as described below. In general, data and pilot may be transmitted using one or more orthonormal matrices such that a receiver is able

to estimate the channel response based on the pilot and use the channel response estimate to recover the data sent to the receiver.

[0042] The permutation matrix $\underline{\mathbf{P}}(k)$ selects which M virtual antennas to use for subcarrier k from among the V virtual antennas available for use, or which M of the V columns of $\underline{\mathbf{U}}$. The permutation matrix $\underline{\mathbf{P}}(k)$ may be defined in various manners, and different permutation matrices may be used for different subcarriers, as described below.

[0043] **FIG. 3** shows a model 300 for the transmission scheme given by equation (3). The transmitter receives the data vector $\underline{\mathbf{s}}(k)$ for each subcarrier and symbol period used for transmission. A virtual antenna mapper 310 processes the data vector $\underline{\mathbf{s}}(k)$ and generates the transmit vector $\underline{\mathbf{x}}(k)$. Within virtual antenna mapper 310, a symbol-to-virtual antenna mapping unit 312 multiplies the data vector $\underline{\mathbf{s}}(k)$ with the permutation matrix $\underline{\mathbf{P}}(k)$ and generates a V×1 intermediate vector. A spatial spreading unit 314 multiplies the intermediate vector with the orthonormal matrix $\underline{\mathbf{U}}$ and generates the transmit vector $\underline{\mathbf{x}}(k)$. The transmit vector $\underline{\mathbf{x}}(k)$ is transmitted from the T transmit antennas and via a MIMO channel 350 to R receive antennas at a receiver.

[0044] The received symbols at the receiver may be expressed as:

$$\begin{aligned}\underline{\mathbf{r}}(k) &= \underline{\mathbf{H}}(k)\cdot\underline{\mathbf{x}}(k)+\underline{\mathbf{n}}(k) \ , \\ &= \underline{\mathbf{H}}(k)\cdot\underline{\mathbf{U}}\cdot\underline{\mathbf{P}}(k)\cdot\underline{\mathbf{s}}(k)+\underline{\mathbf{n}}(k) \ , \\ &= \underline{\mathbf{H}}_{eff}(k)\cdot\underline{\mathbf{P}}(k)\cdot\underline{\mathbf{s}}(k)+\underline{\mathbf{n}}(k) \ , \\ &= \underline{\mathbf{H}}_{used}(k)\cdot\underline{\mathbf{s}}(k)+\underline{\mathbf{n}}(k) \ ,\end{aligned} \qquad \text{Eq (4)}$$

where $\underline{\mathbf{r}}(k)$ is an R×1 vector containing R received symbols from the R receive antennas on subcarrier k in one symbol period;

$\underline{\mathbf{H}}_{eff}(k)$ is an R×V effective channel response matrix for subcarrier k;

$\underline{\mathbf{H}}_{used}(k)$ is an R×M used channel response matrix for subcarrier k; and

$\underline{\mathbf{n}}(k)$ is an R×1 noise vector for subcarrier k.

[0045] The effective and used channel response matrices may be given as:

$$\underline{\mathbf{H}}_{eff}(k) = \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{U}} \ , \\ = [\underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_1 \ \ \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_2 \ \ldots \ \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_V] \ , \text{ and} \qquad \text{Eq (5)}$$

$$\underline{\mathbf{H}}_{used}(k) = \underline{\mathbf{H}}_{eff}(k) \cdot \underline{\mathbf{P}}(k) \ , \\ = [\underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_{(1)} \ \ \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_{(2)} \ \ldots \ \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_{(M)}] \ , \qquad \text{Eq (6)}$$

where $\{\underline{\mathbf{u}}_{(1)} \ \underline{\mathbf{u}}_{(2)} \ \ldots \ \underline{\mathbf{u}}_{(M)}\} \subset \{\underline{\mathbf{u}}_1 \ \underline{\mathbf{u}}_2 \ \ldots \ \underline{\mathbf{u}}_V\}$.

[0046] As shown in equation (3) and illustrated in FIG. 3, an effective MIMO channel with V virtual antennas is formed by the use of the orthonormal matrix $\underline{\mathbf{U}}$. Data is sent on all or a subset of the V virtual antennas. A used MIMO channel is formed by the M virtual antennas used for transmission.

[0047] For the transmission scheme described above, an $R \times T$ MIMO system is effectively reduced to an $R \times V$ MIMO system. The transmitter appears as if it has V virtual antennas rather than T transmit antennas, where $V \leq T$. This transmission scheme decreases the channel estimation overhead order to $C = V$. However, the spatial multiplexing order is limited to V, or $M \leq V$, and the spatial diversity order is also limited to V, or $D \leq V$.

[0048] The description above is for one subcarrier *k*. The transmitter may perform the same processing for each subcarrier used for transmission. The frequency diversity of each virtual antenna across subcarriers is the same as the frequency diversity of the physical transmit antennas. However, the spatial diversity is reduced from T to V.

[0049] In another embodiment, the transmitter processes the output symbols for transmission, as follows:

$$\underline{\tilde{\mathbf{x}}}(k) = \underline{\mathbf{D}}(k) \cdot \underline{\mathbf{U}} \cdot \underline{\mathbf{P}}(k) \cdot \underline{\mathbf{s}}(k) \ , \qquad \text{Eq (7)}$$

where $\underline{\mathbf{D}}(k)$ is a $T \times T$ diagonal matrix for subcarrier *k*. $\underline{\mathbf{D}}(k)$ is used to achieve cyclic delay diversity, which improves the frequency selectivity of the virtual antennas and may improve spatial diversity order to somewhere between V and T. Cyclic delay diversity may be achieved in the time domain or the frequency domain.

[0050] Cyclic delay diversity may be achieved in the time domain by circularly shifting (or cyclically delaying) the sequence of K time-domain samples (obtained from

the K-point IDFT or IFFT) for each transmit antenna i by a delay of T_i, for $i = 1, ..., T$. For example, T_i may be defined as $T_i = (i-1) \cdot J$, where J may be equal to one sample period, a fraction of a sample period, or more than one sample period. J may be selected such that the channel impulse response for each virtual antenna is expected to be shorter than the cyclic prefix length. A cyclic delay of X samples may be achieved by moving the last X samples in the sequence of K time-domain samples to the front of the sequence. The time-domain samples for the T transmits antenna are cyclically delayed by different amounts. A cyclic prefix may be appended after applying the cyclic delay in order to ensure orthogonality among the K total subcarriers.

[0051] Cyclic delay diversity may also be achieved in the frequency domain by applying a phase ramp (or a progressive phase shift) across the K total subcarriers for each transmit antenna. T different phase ramps are used for the T transmit antennas to achieve K different cyclic delays for these antennas. The diagonal matrix $\underline{\mathbf{D}}(k)$ for each subcarrier k may be defined as follows:

$$\underline{\mathbf{D}}(k) = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{j2\pi \cdot (k-1) \cdot J/T} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e^{j2\pi \cdot (k-1) \cdot (T-1) \cdot J/T} \end{bmatrix}, \quad \text{for } k = 1, ..., K. \qquad \text{Eq (8)}$$

As indicated by equation (8), transmit antenna 1 has a phase slope of 0 across the K total subcarriers, transmit antenna 2 has a phase slope of $2\pi \cdot J/T$ across the K total subcarriers, and so on, and transmit antenna T has a phase slope of $2\pi \cdot (T-1) \cdot J/T$ across the K total subcarriers. The diagonal matrix $\underline{\mathbf{D}}(k)$ and the orthonormal matrix $\underline{\mathbf{U}}$ may also be combined to obtain a new orthonormal matrix $\underline{\mathbf{U}}(k) = \underline{\mathbf{D}}(k) \cdot \underline{\mathbf{U}}$, where $\underline{\mathbf{U}}(k)$ may be applied to the data vector $\underline{\mathbf{s}}(k)$.

[0052] The received symbols with cyclic delay diversity may be expressed as:

$$\begin{aligned}\tilde{\underline{r}}(k) &= \underline{\underline{H}}(k)\cdot\tilde{\underline{x}}(k)+\underline{n}(k) \quad , \\ &= \underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{\underline{U}}\cdot\underline{\underline{P}}(k)\cdot\underline{s}(k)+\underline{n}(k) \quad , \\ &= \tilde{\underline{\underline{H}}}_{eff}(k)\cdot\underline{\underline{P}}(k)\cdot\underline{s}(k)+\underline{n}(k) \quad , \\ &= \tilde{\underline{\underline{H}}}_{used}(k)\cdot\underline{s}(k)+\underline{n}(k) \quad ,\end{aligned} \qquad \text{Eq (9)}$$

where $\tilde{\underline{r}}(k)$ is an $R\times 1$ received vector with cyclic delay diversity;

$\tilde{\underline{\underline{H}}}_{eff}(k)$ is an $R\times V$ effective channel response matrix with cyclic delay diversity; and

$\tilde{\underline{\underline{H}}}_{used}(k)$ is an $R\times M$ used channel response matrix with cyclic delay diversity.

[0053] The effective and used channel response matrices may be given as:

$$\begin{aligned}\tilde{\underline{\underline{H}}}_{eff}(k) &= \underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{\underline{U}} \quad , \\ &= [\underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{u}_1 \;\; \underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{u}_2 \;\ldots\; \underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{u}_V] \quad , \text{ and}\end{aligned} \qquad \text{Eq (10)}$$

$$\begin{aligned}\tilde{\underline{\underline{H}}}_{used}(k) &= \tilde{\underline{\underline{H}}}_{eff}(k)\cdot\underline{\underline{P}}(k) \quad , \\ &= [\underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{u}_{(1)} \;\; \underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{u}_{(2)} \;\ldots\; \underline{\underline{H}}(k)\cdot\underline{\underline{D}}(k)\cdot\underline{u}_{(M)}] \quad .\end{aligned} \qquad \text{Eq (11)}$$

[0054] **FIG. 4** shows a model 400 for the transmission scheme given by equation (7). Within a virtual antenna mapper 410, a symbol-to-virtual antenna mapping unit 412 multiplies the data vector $\underline{s}(k)$ with the permutation matrix $\underline{\underline{P}}(k)$ and generates a $V\times 1$ vector. A spatial spreading unit 414 multiplies the $V\times 1$ vector with the orthonormal matrix $\underline{\underline{U}}$ and generates a $T\times 1$ vector. A cyclic delay diversity unit 416 multiplies the $T\times 1$ vector with the diagonal matrix $\underline{\underline{D}}(k)$ and generates the $T\times 1$ transmit vector $\underline{x}(k)$. The transmit vector $\underline{x}(k)$ is transmitted from the T transmit antennas and via a MIMO channel 450 to R receive antennas at a receiver.

[0055] As shown in equation (7) and illustrated in FIG. 4, an effective MIMO channel $\tilde{\underline{\underline{H}}}_{eff}(k)$ with V virtual antennas is formed by the use of the orthonormal matrix $\underline{\underline{U}}$ and cyclic delay diversity. A used MIMO channel $\tilde{\underline{\underline{H}}}_{used}(k)$ is formed by the M virtual antennas used for transmission.

[0056] Equations (3) and (7) assume that equal transmit power is used for the M output symbols being sent simultaneously on one subcarrier in one symbol period. In general, the transmit power available for each transmit antenna may be uniformly or non-uniformly distributed across the subcarriers used for transmission. The transmit powers available for the T transmit antennas for each subcarrier may be uniformly or non-uniformly distributed to the M output symbols being sent on that subcarrier. Different transmit powers may be used for the M output symbols by scaling the data vector $\underline{\mathbf{s}}(k)$ with a diagonal gain matrix $\underline{\mathbf{G}}$ as follows: $\underline{\mathbf{x}}(k) = \underline{\mathbf{U}} \cdot \underline{\mathbf{P}}(k) \cdot \underline{\mathbf{G}} \cdot \underline{\mathbf{s}}(k)$ or $\underline{\tilde{\mathbf{x}}}(k) = \underline{\mathbf{D}}(k) \cdot \underline{\mathbf{U}} \cdot \underline{\mathbf{P}}(k) \cdot \underline{\mathbf{G}} \cdot \underline{\mathbf{s}}(k)$, where $\text{diag}\{\underline{\mathbf{G}}\} = \{g_1 \ g_2 \ \ldots \ g_M\}$ and g_i is the gain for output symbol s_i.

[0057] Various types of matrices may be used to form the orthonormal matrix $\underline{\mathbf{U}}$. For example, $\underline{\mathbf{U}}$ may be formed based on a Fourier matrix, a Walsh matrix, or some other matrix. A T×T Fourier matrix $\underline{\mathbf{F}}_{T\times T}$ has element $f_{n,m}$ in the *n*-th row of the *m*-th column, which may be expressed as:

$$f_{n,m} = e^{-j2\pi\frac{(n-1)(m-1)}{T}}, \quad \text{for } n = 1, \ldots, T \text{ and } m = 1, \ldots, T. \qquad \text{Eq (12)}$$

Fourier matrices of any square dimension (e.g., 2, 3, 4, 5, 6, and so on) may be formed. A 2×2 Walsh matrix $\underline{\mathbf{W}}_{2\times 2}$ and larger size Walsh matrix $\underline{\mathbf{W}}_{2N\times 2N}$ may be expressed as:

$$\underline{\mathbf{W}}_{2\times 2} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad \text{and} \quad \underline{\mathbf{W}}_{2N\times 2N} = \begin{bmatrix} \underline{\mathbf{W}}_{N\times N} & \underline{\mathbf{W}}_{N\times N} \\ \underline{\mathbf{W}}_{N\times N} & -\underline{\mathbf{W}}_{N\times N} \end{bmatrix}. \qquad \text{Eq (13)}$$

[0058] In an embodiment, the orthonormal matrix $\underline{\mathbf{U}}$ is equal to a matrix containing V columns of a T×T Fourier matrix or a T×T Walsh matrix. In another embodiment, $\underline{\mathbf{U}}$ is formed as follows:

$$\underline{\mathbf{U}} = \underline{\Delta} \cdot \underline{\mathbf{F}}, \qquad \text{Eq (14)}$$

where $\underline{\mathbf{F}}$ is a T×V matrix containing the first V columns of the T×T Fourier matrix; and $\underline{\Delta}$ is a T×T diagonal matrix containing T scaling values for the T rows of $\underline{\mathbf{F}}$.

For example, the diagonal matrix $\underline{\Delta}$ may be defined as $\underline{\Delta} = \text{diag}\{1\ e^{j\theta_1}\ \ldots\ e^{j\theta_T}\}$, where θ_i for $i = 1, \ldots, T$ may be random phases. Equation (14) multiplies the rows of $\underline{\mathbf{F}}$ with random phases, which changes the spatial directions depicted by the columns of $\underline{\mathbf{F}}$. In yet another embodiment, $\underline{\mathbf{U}}$ is an orthonormal matrix with pseudo-random elements, e.g., having unit magnitude and pseudo-random phases.

[0059] The transmitter may send a MIMO, SIMO or SISO transmission to a receiver on a set of subcarriers, which are called the assigned subcarriers. The K total subcarriers may be partitioned into multiple non-overlapping subcarrier sets. In this case, the transmitter may transmit to multiple receivers simultaneously on multiple subcarrier sets. The transmitter may send the same or different types of transmission to these multiple receivers. For example, the transmitter may send a MIMO transmission on a first subcarrier set to a first receiver, a SIMO transmission on a second subcarrier set to a second receiver, a SISO transmission on a third subcarrier set to a third receiver, and so on.

[0060] A SIMO or SISO transmission may be sent from a single virtual antenna formed with a single column of the orthonormal matrix $\underline{\mathbf{U}}$. In this case, $M = V = 1$, and the effective MIMO channel becomes an $R \times 1$ SISO or SIMO channel having a channel response vector of $\underline{\mathbf{h}}_{eff}(k) = \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{u}}_1$ or $\underline{\tilde{\mathbf{h}}}_{eff}(k) = \underline{\mathbf{H}}(k) \cdot \underline{\mathbf{D}}(k) \cdot \underline{\mathbf{u}}_1$. The data vector $\underline{\mathbf{s}}(k)$ becomes a 1×1 vector containing a single output symbol, the permutation matrix $\underline{\mathbf{P}}(k)$ becomes a 1×1 matrix containing a single '1', and the orthonormal matrix $\underline{\mathbf{U}}$ becomes a $T \times 1$ matrix containing a single column.

[0061] A MIMO transmission may be sent from multiple virtual antennas formed with multiple columns of the orthonormal matrix $\underline{\mathbf{U}}$. If the number of output symbols is less than the number of virtual antennas (or $M < S$), then M virtual antennas may be selected for use in various manners.

[0062] **FIG. 5** shows an embodiment for transmitting output symbols cyclically from the V virtual antennas. For this embodiment, the first M output symbols are sent from virtual antennas 1 through M on the first assigned subcarrier, the next M output symbols are sent from virtual antennas 2 through $M+1$ on the next assigned subcarrier, and so on. The assigned subcarriers may be given indices of $k = 1, 2, \ldots$. For the embodiment shown in FIG. 5, the M virtual antennas used for subcarrier $k+1$ are offset

by one from the M virtual antennas used for subcarrier k. The selected virtual antennas wrap around to virtual antenna 1 upon reaching the last virtual antenna. Hence, virtual antennas $((k-1) \bmod V)+1$ through $((k+M-2) \bmod V)+1$ are used for assigned subcarrier k, where "mod S" denotes a modulo-S operation and the "–1" and "+1" are due to the index for the assigned subcarriers and the index for the virtual antennas starting with 1 instead of 0. The M columns of the permutation matrix $\underline{\mathbf{P}}(k)$ for each assigned subcarrier k are the $((k-1,\ k,\ k+1,\ ...,\ k+M-2) \bmod V)+1$ columns of a $V \times V$ identify matrix. For example, if $M=2$ and $V=3$, then the permutation matrices may be defined as:

$$\underline{\mathbf{P}}(1)=\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 0\end{bmatrix},\ \underline{\mathbf{P}}(2)=\begin{bmatrix}0 & 0\\ 1 & 0\\ 0 & 1\end{bmatrix},\ \underline{\mathbf{P}}(3)=\begin{bmatrix}0 & 1\\ 0 & 0\\ 1 & 0\end{bmatrix},\ \underline{\mathbf{P}}(4)=\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 0\end{bmatrix}, \text{ and so on.} \quad \text{Eq (15)}$$

[0063] In another embodiment, the first M output symbols are sent from virtual antennas 1 through M on the first assigned subcarrier, the next M output symbols are sent from virtual antennas $M+1$ through $((2M-1) \bmod V)+1$ on the next assigned subcarrier, and so on. For this embodiment, the M virtual antennas used for subcarrier $k+1$ start after the last virtual antenna used for subcarrier k. In yet another embodiment, the M virtual antennas for each subcarrier are selected in a pseudo-random manner, e.g., based on a pseudo-random number (PN) generator or sequence that is also known to the receiver.

[0064] In yet another embodiment, the virtual antennas are selected based on feedback from a receiver. For example, the feedback may indicate the specific virtual antennas to use for all assigned subcarriers, the specific virtual antennas to use for each assigned subcarrier, and so on. In yet another embodiment, the transmitter may select the virtual antennas based on a pilot or some other transmission received from the receiver. For example, the transmitter may estimate the uplink channel response based on the received pilot, estimate the downlink channel response based on the uplink channel response estimate, and select the virtual antennas based on the downlink channel response estimate. The downlink and uplink channel responses may be similar, e.g., in a time division duplexed (TDD) system in which downlink and uplink transmissions are sent on the same frequency channel but in different time intervals.

[0065] In general, the virtual antennas may be selected (1) by the transmitter in a deterministic manner (e.g., cyclically) or a pseudo-random manner without feedback from the receiver, (2) by the transmitter based on feedback from receiver, or (3) by the receiver and sent to the transmitter.

[0066] The orthonormal matrix $\underline{U}$ may be fixed, and the V virtual antennas formed with $\underline{U}$ may be selected for use as described above. In another embodiment, one or more orthonormal matrices are selected for use from among a set of orthonormal matrices available for use. The set of orthonormal matrices forms a codebook, and one or more entries of the codebook may be used for transmission. The orthonormal matrices in the set are different (and may be pseudo-random) with respect to each other. For example, the orthonormal matrices may be defined to provide good performance for different channel conditions, e.g., low and high SNR conditions, low and high mobility, and so on. One orthonormal matrix may be selected for all assigned subcarriers, for each assigned subcarrier, and so on. The matrix selection may be made (1) by the transmitter with or without feedback from a receiver or (2) by the receiver and sent back to the transmitter. The matrix selection may be made based on various factors such as, e.g., the channel conditions, mobility, uplink resources, and so on. In general, the particular entry or entries in the codebook to use for transmission may be selected either autonomously by the transmitter or based on feedback from the receiver.

[0067] The transmission schemes described herein has the following desirable features:

- Flexibility to easily select the number of virtual antennas;
- Flexibility to send any number of output symbols up to the number of available virtual antennas; and
- Utilization of all T transmit antennas for transmission regardless of the number of output symbols being sent and the number of available virtual antennas.

[0068] The number of virtual antennas (V) may be selected to support the desired spatial multiplexing order (M), to achieve the desired spatial diversity order (D), and to obtain the desired channel estimation overhead order (C). The number of virtual antennas may be selected autonomously by the transmitter or based on a feedback from the receiver. The desired number of virtual antennas may readily be obtained by defining the orthonormal matrix $\underline{U}$ with the proper number of columns.

[0069] The spatial multiplexing order is limited by the number of transmit antennas and the number of receive antennas, or $M \leq \min\{T, R\}$. A higher spatial multiplexing order may be desirable in certain scenarios (e.g., high SNR conditions) and if supported by the receiver. A lower spatial multiplexing order (e.g., $M = 1$) may be desirable in other scenarios (e.g., low SNR conditions) or if a higher spatial multiplexing order is not supported by the receiver. The spatial multiplexing order may be dynamically selected based on the channel conditions and/or other factors. For example, the spatial multiplexing order may be set to one if the SNR is less than a first threshold, set to two if the SNR is between the first threshold and a second threshold, set to three if the SNR is between the second threshold and a third threshold, and so on. The number of virtual antennas is selected to be equal to or greater than the spatial multiplexing order, or $V \geq M$.

[0070] In general, a higher spatial diversity order is desirable in order to improve performance, and a lower channel estimation overhead order is desirable in order to reduce the amount of link resources used to transmit a pilot for channel estimation. The channel estimation overhead order is closely related to the spatial diversity order, and both are determined by the number of virtual antennas. Hence, the number of virtual antennas may be dynamically selected based on the desired spatial diversity order, the desired channel estimation overhead order, the channel conditions, and/or other factors.

[0071] The number of virtual antennas may be selected in various manners. In an embodiment, the number of virtual antennas is set equal to the spatial multiplexing order, or $V = M$. In another embodiment, the number of virtual antennas is set to a largest possible value such that the link resources used for pilot transmission is maintained within a predetermined percentage of the total link resources. In yet another embodiment, the number of virtual antennas is set based on the channel conditions. For example, one virtual antenna may be defined if the SNR is less than a first value, two virtual antennas may be defined if the SNR is between the first value and a second value, and so on.

[0072] The transmission schemes described herein may be used with various subcarrier structures, some of which are described below. The following description assumes that the K total subcarriers are usable for transmission and are given indices of 1 through K.

[0073] **FIG. 6A** shows an interlace subcarrier structure 600. For this subcarrier structure, the K total subcarriers are arranged into S non-overlapping interlaces, each interlace contains N subcarriers that are uniformly distributed across the K total subcarriers, and consecutive subcarriers in each interlace are spaced apart by S subcarriers, where $K = S \cdot N$. Interlace u contains subcarrier u as the first subcarrier, where $u \in \{1, ..., S\}$.

[0074] **FIG. 6B** shows a block subcarrier structure 610. For this subcarrier structure, the K total subcarriers are arranged into S non-overlapping blocks, with each block containing N adjacent subcarriers, where $K = S \cdot N$. Block v contains subcarriers $v \cdot N + 1$ through $(v+1) \cdot N$, where $v \in \{1, ..., S\}$.

[0075] **FIG. 6C** shows a group subcarrier structure 620. For this subcarrier structure, the K total subcarriers are arranged into S non-overlapping groups, each group contains G subgroups that are distributed across the system bandwidth, and each subgroup contains L adjacent subcarriers, where $K = S \cdot N$ and $N = G \cdot L$. The K total subcarriers may be partitioned into G frequency ranges, with each frequency range containing $S \cdot L$ consecutive subcarriers. Each frequency range is further partitioned into S subgroups, with each subgroup containing L consecutive subcarriers. For each frequency range, the first L subcarriers are allocated to group 1, the next L subcarriers are allocated to group 2, and so on, and the last L subcarriers are allocated to group S. Each group contains G subgroups of L consecutive subcarriers, or a total of $N = G \cdot L$ subcarriers.

[0076] In general, the transmission techniques described herein may be used for any subcarrier structure with any number of subcarrier sets. Each subcarrier set may include any number of subcarriers that may be arranged in any manner. For example, a subcarrier set may be equal to an interlace, a subcarrier block, a subcarrier group, and so on. For each subcarrier set, (1) the subcarriers in the set may be uniformly or non-uniformly distributed across the system bandwidth, (2) the subcarriers in the set may be adjacent to one another in one group, or (3) the subcarriers in the set may be distributed in multiple groups, where each group may be located anywhere within the system bandwidth and may contain one or multiple subcarriers.

[0077] For all of the subcarrier structures described above, different receivers may be assigned different subcarrier sets, and the transmitter may transmit data to each

receiver on its assigned subcarrier set. The transmitter may use the same orthonormal matrix $\underline{U}$ for all receivers, a different orthonormal matrix for each receiver, a different orthonormal matrix for each subcarrier set, a different orthonormal matrix for each subcarrier, and so on.

[0078] The transmission techniques described herein may be used with or without frequency hopping. With frequency hopping, the data transmission hops from subcarrier to subcarrier in a pseudo-random or deterministic manner over time, which allows the data transmission to better withstand deleterious channel conditions such as narrowband interference, jamming, fading, and so on. Frequency hopping can provide frequency diversity and interference randomization. A receiver may be assigned a traffic channel that is associated with a hop pattern that indicates which subcarrier set(s), if any, to use in each time slot. A hop pattern is also called a frequency hopping pattern or sequence. A time slot is the amount of time spent on a given subcarrier set and is also called a hop period. The hop pattern may select different subcarrier sets in different time slots in a pseudo-random or deterministic manner.

[0079] **FIG. 7** shows an exemplary frequency hopping scheme 700. In FIG. 7, traffic channel 1 is mapped to a specific sequence of time-frequency blocks. Each time-frequency block is a specific subcarrier set in a specific time slot. In the example shown in FIG. 7, traffic channel 1 is mapped to subcarrier set 1 in time slot 1, subcarrier set 4 in time slot 2, and so on. Traffic channels 2 through S may be mapped to vertically and circularly shifted versions of the time-frequency block sequence for traffic channel 1. For example, traffic channel 2 may be mapped to subcarrier set 2 in time slot 1, subcarrier set 5 in time slot 2, and so on.

[0080] Frequency hopping may be used with any of the subcarrier structures shown in FIGS. 6A through 6C. For example, a symbol rate hopping scheme may be defined in which each time-frequency block is a specific interlace in one symbol period. For this hopping scheme, the assigned subcarriers span across the entire system bandwidth and change from symbol period to symbol period. As another example, a block hopping scheme may be defined in which each time-frequency block is a specific subcarrier block in a time slot of multiple symbol periods. For this hopping scheme, the assigned subcarriers are contiguous and fixed for an entire time slot but changes from time slot to time slot. For the block hopping scheme, the spatial multiplexing order may be set

equal to the number of virtual antennas, so that constant interference may be observed on any given time-frequency block in any sector for a system with synchronous sectors. Other hopping scheme may also be defined.

[0081] Pilot may be transmitted in various manners with the subcarrier structures described above. Some exemplary pilot schemes for symbol rate hopping and block hopping are described below.

[0082] **FIG. 8** shows an exemplary pilot scheme 800 for symbol rate hopping. For pilot scheme 800, the transmitter transmits a common pilot on one interlace from virtual antenna 1 in each symbol period. The transmitter may transmit the common pilot on different interlaces in different symbol periods, as shown in FIG. 8. Such a staggered pilot allows a receiver to sample the frequency spectrum on more subcarriers and to derive a longer channel impulse response estimate. The transmitter may also transmit an auxiliary pilot on one or more interlaces from the remaining virtual antennas to allow MIMO receivers to estimate the channel response for all virtual antennas used for transmission. For the embodiment shown in FIG. 8, the transmitter transmits the auxiliary pilot on one interlace in each symbol period and cycles through virtual antennas 2 through V in $V-1$ different symbol periods. For the case with $V=4$ as shown in FIG. 8, the transmitter transmits the auxiliary pilot from virtual antenna 2 in symbol period $n+1$, then from virtual antenna 3 in symbol period $n+2$, then from virtual antenna 4 in symbol period $n+3$, then from virtual antenna 2 in symbol period $n+4$, and so on.

[0083] The transmitter may transmit the common and auxiliary pilots in other manners. In another embodiment, the auxiliary pilot is staggered and sent on different sets of subcarriers. In yet another embodiment, the common pilot is sent on one or more subcarrier sets that are pseudo-random (or have random offsets) with respect to the one or more subcarrier sets used for the auxiliary pilot.

[0084] The transmitter may transmit the common pilot for MIMO, SIMO and SISO receivers and may transmit the auxiliary pilot only when MIMO receivers are present. The MIMO, SIMO and SISO receivers may use the common pilot to derive a channel estimate for the K total subcarriers of virtual antenna 1. A MIMO receiver may use the auxiliary pilot to derive channel estimates for virtual antennas 2 through V.

[0085] **FIG. 9A** shows an exemplary pilot scheme 910 for block hopping. For the embodiment shown in FIG. 9A, a time-frequency block is composed of 16 adjacent subcarriers $k+1$ through $k+16$ and further spans 8 symbol periods $n+1$ through $n+8$. For pilot scheme 910, the transmitter transmits a dedicated pilot on subcarriers $k+3$, $k+9$ and $k+15$ in each of symbol periods $n+1$ through $n+3$ and $n+6$ through $n+8$, or six strips of three pilot symbols. Each pilot symbol may be sent from any virtual antenna. For example, if $V=3$, then the transmitter may transmit the pilot from virtual antenna 1 in symbol periods $n+1$ and $n+6$, from virtual antenna 2 in symbol periods $n+2$ and $n+7$, and from virtual antenna 3 in symbol periods $n+3$ and $n+8$.

[0086] **FIG. 9B** shows an exemplary pilot scheme 920 for block hopping. For pilot scheme 920, the transmitter transmits a dedicated pilot on subcarriers $k+3$, $k+9$ and $k+15$ in each of symbol periods $n+1$ through $n+8$, or three strips of eight pilot symbols. Each pilot symbol may be sent from any virtual antenna. For example, if $V=4$, then the transmitter may transmit the pilot from virtual antenna 1 in symbol periods $n+1$ and $n+5$, from virtual antenna 2 in symbol periods $n+2$ and $n+6$, from virtual antenna 3 in symbol periods $n+3$ and $n+7$, and from virtual antenna 4 in symbol periods $n+4$ and $n+8$.

[0087] **FIG. 9C** shows an exemplary pilot scheme 930 for block hopping. For pilot scheme 930, the transmitter transmits a dedicated pilot on subcarriers $k+1$, $k+4$, $k+7$, $k+10$, $k+13$ and $k+16$ in each of symbol periods $n+1$, $n+2$, $n+7$ and $n+8$. Each pilot symbol may be sent from any virtual antenna. For example, the transmitter may transmit the pilot from virtual antenna 1 in symbol period $n+1$, from virtual antenna 2 in symbol period $n+2$, from virtual antenna 1 or 3 in symbol period $n+7$, and from virtual antenna 2 or 4 in symbol period $n+8$.

[0088] **FIG. 9D** shows an exemplary pilot scheme 940 for block hopping. For pilot scheme 940, the transmitter transmits a staggered pilot on three subcarriers in each symbol period and on different pilot subcarriers in different symbol periods. Each pilot symbol may be sent from any virtual antenna. For example, the transmitter may transmit the pilot from a different virtual antenna in each symbol period and may cycle through the V virtual antennas in V symbol periods.

[0089] In general, for the block hopping scheme, the transmitter may transmit a pilot in each time-frequency block such that a receiver is able to derive a channel estimate for each virtual antenna used for transmission. FIGS. 9A through 9D show four exemplary pilot patterns that may be used. Other pilot patterns may also be defined and used for pilot transmission.

[0090] For both symbol rate hopping and block hopping, the transmitter may transmit the pilot from any number of virtual antennas, may use any number of pilot subcarriers for each virtual antenna, and may use any amount of transmit power for each virtual antenna. If the pilot is sent from multiple virtual antennas, then the transmitter may use the same or different numbers of subcarriers for these virtual antennas and may transmit the pilot at the same or different power levels for the virtual antennas. The transmitter may or may not stagger the pilot for each virtual antenna. The transmitter may transmit the pilot on more subcarriers to allow a receiver to obtain more "look" of the wireless channel in the frequency domain and to derive a longer channel impulse response estimate. The transmitter may transmit the pilot on all pilot subcarriers from one virtual antenna in each symbol period, as described above. Alternatively, the transmitter may transmit the pilot from multiple virtual antennas on multiple subsets of subcarriers in a given symbol period.

[0091] In an embodiment, the transmitter transmits the pilot from the virtual antennas, as described above for FIGS. 8 through 9D. In another embodiment, the transmitter transmits the pilot from the physical antennas, without applying the orthonormal matrix $\underline{\mathbf{U}}$ or the permutation matrix $\underline{\mathbf{P}}(k)$. For this embodiment, a receiver may estimate the actual channel response based on the pilot and may then derive an effective channel response estimate based on the actual channel response estimate and the orthonormal and permutation matrices.

[0092] **FIG. 10** shows a process 1000 for transmitting data and pilot to one or more receivers. The processing for each receiver may be performed as follows. The set of subcarriers assigned to the receiver and the spatial multiplexing order (M) for the receiver are determined, where $M \geq 1$ (block 1012). For each assigned subcarrier, M virtual antennas are selected for use from among V virtual antennas formed with V columns of the orthonormal matrix $\underline{\mathbf{U}}$, where $V \geq M$ (block 1014). The M virtual antennas for each assigned subcarrier may be selected in various manners, as described

above. The output symbols for the receiver are mapped to the M virtual antennas selected for each assigned subcarrier by applying the orthonormal matrix (block 1016). The mapped output symbols (or transmit symbols) are provided for transmission from T transmit antennas, where $T \geq V$ (block 1018).

[0093] Pilot symbols are also mapped to the virtual antennas used for transmission (block 1020). For example, pilot symbols for a common pilot may be mapped to the first virtual antenna on a first set of pilot subcarriers, and pilot symbols for an auxiliary pilot may be mapped to the remaining virtual antennas on a second set of pilot subcarriers.

[0094] If there are multiple receivers, then the same or different spatial multiplexing orders may be used for these receivers. Furthermore, data may be sent simultaneously on different subcarrier sets to multiple receivers. For example, data may be sent from one virtual antenna on a first subcarrier set to a SIMO or SISO receiver, from multiple virtual antennas on a second subcarrier set to a MIMO receiver, and so on. In any case, the transmit symbols for all receivers are demultiplexed to the T transmit antennas (block 1022). For each transmit antenna, the transmit symbols for each receiver are mapped to the subcarriers assigned to that receiver (also block 1022). Transmission symbols are then generated for each transmit antenna based on the transmit symbols for that transmit antenna and using, e.g., OFDM or SC-FDMA (block 1024). Different cyclic delays may be applied for the T transmit antennas, e.g., by circularly delaying the transmission symbols for each transmit antenna by a different amount (block 1026).

[0095] For block 1016 in FIG. 10, the output symbol(s) for each subcarrier assigned to each receiver are mapped to the T transmit antennas based on M mapping patterns selected from among V mapping patterns available for use. Each mapping pattern indicates a specific mapping of an output symbol to the T transmit antennas. The V mapping patterns may be formed by V columns of an orthonormal matrix or in other manners. Different mapping patterns may be selected for different subcarriers in a given symbol period and/or different symbol periods, e.g., based on a predetermined pattern. The predetermined pattern may be defined by a permutation matrix or in some other manner. The predetermined pattern may cycle through the V available mapping patterns in different subcarriers and/or symbol periods.

[0096] **FIG. 11** shows an embodiment of an apparatus 1100 for transmitting data and pilot to one or more receivers. Apparatus 1100 includes means for determining the

set of subcarriers assigned to each receiver and the spatial multiplexing order (M) for each receiver (block 1112), means for selecting M virtual antennas for use from among V virtual antennas for each subcarrier assigned to each receiver (block 1114), means for mapping the output symbols for each receiver to the virtual antennas selected for each subcarrier assigned to the receiver (e.g., by applying selected columns of an orthonormal matrix or selected mapping patterns) (block 1116), means for providing the mapped output symbols (or transmit symbols) for transmission from T transmit antennas (block 1118), means for mapping pilot symbols to the virtual antennas used for transmission (block 1120), means for demultiplexing the transmit symbols for each receiver to the assigned subcarriers of the T transmit antennas (block 1122), means for generating transmission symbols for each transmit antenna, e.g., using OFDM or SC-FDMA (block 1124), and means for applying different cyclic delays for the T transmit antennas (block 1126).

[0097] **FIG. 12** shows a block diagram of an embodiment of base station 110, single-antenna terminal 120x, and multi-antenna terminal 120y. At base station 110, a transmit (TX) data processor 1210 receives data for one or more terminals, processes (e.g., encodes, interleaves, and symbol maps) the data based on one or more coding and modulation schemes, and provides modulation symbols. TX data processor 1210 typically processes the data for each terminal separately based on a coding and modulation scheme selected for that terminal. If system 100 utilizes SC-FDMA, then TX data processor 1210 may perform FFT/DFT on the modulation symbols for each terminal to obtain frequency-domain symbols for that terminal. TX data processor 1210 obtains output symbols for each terminal (which may be modulation symbols for OFDM or frequency-domain symbols for SC-FDMA) and multiplexes the output symbols for the terminal onto the subcarriers and virtual antennas used for that terminal. TX data processor 1210 further multiplexes pilot symbols onto the subcarriers and virtual antennas used for pilot transmission.

[0098] A TX spatial processor 1220 receives the multiplexed output symbols and pilot symbols, performs spatial processing for each subcarrier, e.g., as shown in equation (3) or (7), and provides transmit symbols for the T transmit antennas. A modulator (Mod) 1222 processes the transmit symbols for each transmit antenna, e.g., for OFDM, SC-FDMA, or some other modulation technique, and generates an output sample stream for that transmit antenna. Since TX spatial processor 1220 performs

spatial processing for each subcarrier, the SC-FDMA modulation is divided into two parts that are performed by TX data processor 1210 and modulator 1222. Modulator 1222 provides T output sample streams to T transmitter units (TMTR) 1224a through 1224t. Each transmitter unit 1224 processes (e.g., converts to analog, amplifies, filters, and frequency upconverts) its output sample stream and generates a modulated signal. T modulated signals from transmitter units 1224a through 1224t are transmitted from T antennas 112a through 112t, respectively.

[0099] At each terminal 120, one or multiple antennas 122 receive the modulated signals transmitted by base station 110, and each antenna provides a received signal to a respective receiver unit (RCVR) 1254. Each receiver unit 1254 processes (e.g., amplifies, filters, frequency downconverts, and digitalizes) its receive signal and provides received samples to a demodulator (Demod) 1256. Demodulator 1256 processes the received samples for each receive antenna 122 (e.g., based on OFDM, SC-FDMA, or some other modulation technique), obtains frequency-domain received symbols for the K total subcarriers, provides received symbols for the assigned subcarriers, and provides received pilot symbols for the subcarriers used for pilot transmission.

[00100] For single-antenna terminal 120x, a data detector 1260x obtains received symbols from demodulator 1256x, derives channel estimates for the assigned subcarriers based on the received pilot symbols, and performs data detection (e.g., equalization) on the received symbols based on the channel estimates to obtain detected symbols, which are estimates of the output symbols transmitted to terminal 120x. For multi-antenna terminal 120y, a receive (RX) spatial processor 1260y obtains received symbols from demodulator 1256y, derives channel estimates for the assigned subcarriers based on the received pilot symbols, and performs receiver spatial processing on the received symbols based on the channel estimates to obtain detected symbols. RX spatial processor 1260y may implement a minimum mean square error (MMSE) technique, a zero-forcing (ZF) technique, a maximal ratio combining (MRC) technique, a successive interference cancellation technique, or some other receiver processing technique. For each terminal, an RX data processor 1262 processes (e.g., symbol demaps, deinterleaves, and decodes) the detected symbols and provides decoded data for the terminal. In general, the processing by each terminal 120 is complementary to the processing by base station 110.

[00101] Each terminal 120 may generate feedback information for the data transmission to that terminal. For example, each terminal 120 may estimate the SNRs for the virtual antennas, e.g., based on the received pilot symbols. Each terminal 120 may select one or more coding and modulation schemes, one or more packet formats, one or more virtual antennas to use for data transmission, one or more orthonormal matrices, and so on based on the SNR estimates and/or other information. Each terminal 120 may also generate acknowledgments (ACKs) for correctly received data packets. The feedback information may include the SNR estimates, the selected coding and modulation schemes, the selected virtual antenna(s), the selected orthonormal matrix(ces), the selected subcarrier(s), ACKs, information used for power control, some other information, or any combination thereof. The feedback information is processed by a TX data processor 1280, further processed by a TX spatial processor 1282 if multiple antennas are present, modulated by a modulator 1284, conditioned by transmitter unit(s) 1254, and transmitted via antenna(s) 122 to base station 110. At base station 110, the modulated signals transmitted by terminals 120x and 120y are received by antennas 112, conditioned by receiver units 1224, and processed by a demodulator 1240, an RX spatial processor 1242, and an RX data processor 1244 to recover the feedback information sent by the terminals. A controller/processor 1230 uses the feedback information to determine the data rates and coding and modulation schemes to use for the data transmission to each terminal as well as to generate various controls for TX data processor 1210 and TX spatial processor 1220.

[00102] Controllers/processors 1230, 1270x and 1270y control the operation of various processing units at base station 110 and terminals 120x and 120y, respectively. Memory units 1232, 1272x and 1272y store data and program codes used by base station 110 and terminals 120x and 120y, respectively. Controller/processor 1230 may implement parts of FIGS. 10 and 11 and may (1) assign subcarriers and select the spatial multiplexing order for each terminal (block 1012 in FIG. 10) and (2) select the virtual antennas for each subcarrier assigned to each terminal (block 1214 in FIG. 10). TX data processor 1220 may implement parts of FIGS. 10 and 11 and perform the processing shown in blocks 1116 through 1126 in FIG. 10.

[00103] For clarity, much of the description above is for a system with K total subcarriers. The transmission techniques described herein may also be used for a

system with a single subcarrier. For such a system, k in the description above may be an index for symbol period instead of subcarrier.

[00104] The transmission techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, firmware, software, or a combination thereof. For a hardware implementation, the processing units at a transmitter may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, electronic devices, other electronic units designed to perform the functions described herein, or a combination thereof. The processing units at a receiver may also be implemented within one or more ASICs, DSPs, processors, and so on.

[00105] For a software implementation, the transmission techniques may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in a memory (e.g., memory 1230, 1272x or 1272y in FIG. 12) and executed by a processor (e.g., processor 1232, 1270x or 1270y). The memory may be implemented within the processor or external to the processor.

[00106] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[00107] WHAT IS CLAIMED IS:

CLAIMS

1. An apparatus comprising:

at least one processor configured to select M virtual antennas to use for transmission from among V virtual antennas, to map output symbols to the M virtual antennas, and to provide the mapped output symbols for transmission from T transmit antennas, wherein M is equal to one or greater, V is equal to or greater than M, and T is equal to or greater than V; and

a memory coupled to the at least one processor.

2. The apparatus of claim 1, wherein the at least one processor is configured to select different sets of M virtual antennas for different frequency subcarriers from among the V virtual antennas.

3. The apparatus of claim 1, wherein the at least one processor is configured to select a set of M virtual antennas for each of a plurality of frequency subcarriers by cycling through the V virtual antennas.

4. The apparatus of claim 1, wherein the at least one processor is configured to form a permutation matrix indicative of the M virtual antennas selected from among the V virtual antennas, to apply the permutation matrix to the output symbols, and to applying an orthonormal matrix used to form the V virtual antennas.

5. The apparatus of claim 1, wherein the at least one processor is configured to select one virtual antenna from among the V virtual antennas for a first receiver assigned with a first set of frequency subcarriers, to select more than one virtual antenna from among the V virtual antennas for a second receiver assigned with a second set of frequency subcarriers, to map output symbols for the first receiver to the first set of frequency subcarriers of the one virtual antenna, and to map output symbols for the second receiver to the second set of frequency subcarriers of the more than one virtual antenna.

6. The apparatus of claim 1, wherein the at least one processor is configured to apply T different cyclic delays for the T transmit antennas.

7. The apparatus of claim 1, wherein the at least one processor is configured to scale output symbols for the M virtual antennas with M gains.

8. The apparatus of claim 1, wherein the at least one processor is configured to transmit a first pilot on a first virtual antenna among the V virtual antennas, and to transmit a second pilot on remaining ones of the V virtual antennas.

9. The apparatus of claim 8, wherein the at least one processor is configured to transmit the first pilot on a first set of frequency subcarriers of the first virtual antenna, and to transmit the second pilot on a second set of frequency subcarriers by cycling through the remaining ones of the V virtual antennas.

10. The apparatus of claim 1, wherein the at least one processor is configured to transmit pilot symbols on at least one frequency subcarrier in at least one symbol period selected based on a pilot pattern.

11. The apparatus of claim 1, wherein the at least one processor is configured to select an orthonormal matrix from among a plurality of orthonormal matrices available to form the V virtual antennas.

12. The apparatus of claim 1, wherein the at least one processor is configured to receive feedback selecting an orthonormal matrix from among a plurality of orthonormal matrices available to form the V virtual antennas.

13. The apparatus of claim 1, wherein the at least one processor is configured to generate orthogonal frequency division multiplexing (OFDM) symbols for the T transmit antennas based on the mapped output symbols.

14. The apparatus of claim 1, wherein the at least one processor is configured to generate single-carrier frequency division multiple access (SC-FDMA) symbols for the T transmit antennas based on the mapped output symbols.

15. The apparatus of claim 1, wherein the at least one processor is configured to dynamically select M based on channel conditions.

16. The apparatus of claim 1, wherein the at least one processor is configured to dynamically select V based on channel conditions.

17. The apparatus of claim 1, wherein an orthonormal matrix, used to form the V virtual antennas, is defined such that equal transmit power is used for the T transmit antennas.

18. The apparatus of claim 1, wherein an orthonormal matrix, used to form the V virtual antennas, is based on a Fourier matrix or a Walsh matrix.

19. The apparatus of claim 1, wherein an orthonormal matrix, used to form the V virtual antennas is based upon scaling a Fourier matrix or a Walsh matrix with different random phases.

20. A method comprising:

selecting M virtual antennas to use for transmission from among V virtual antennas, wherein M is one or greater and V is equal to or greater than M;

mapping output symbols to the M virtual antennas; and

providing the mapped output symbols for transmission from T transmit antennas, wherein T is equal to or greater than V.

21. The method of claim 20, further comprising:

selecting different sets of M virtual antennas for different frequency subcarriers from among the V virtual antennas.

22. The method of claim 20, further comprising:

applying T different cyclic delays for the T transmit antennas.

23. The method of claim 20, further comprising:

transmitting a pilot on the M virtual antennas.

24. An apparatus comprising:

means for selecting M virtual antennas to use for transmission from among V virtual antennas, wherein M is one or greater and V is equal to or greater than M;

means for mapping output symbols to the M virtual antennas; and

means for providing the mapped output symbols for transmission from T transmit antennas, wherein T is equal to or greater than V.

25. The apparatus of claim 24, further comprising:

means for selecting different sets of M virtual antennas for different frequency subcarriers from among the V virtual antennas.

26. The apparatus of claim 24, further comprising:

means for applying T different cyclic delays for the T transmit antennas.

27. The apparatus of claim 24, further comprising:

means for transmitting a pilot on the M virtual antennas.

28. An apparatus comprising:

at least one processor configured to select M1 virtual antennas to use for transmission to a first receiver from among V virtual antennas, to select M2 virtual antennas to use for transmission to a second receiver from among the V virtual antennas, to map output symbols for the first receiver to the M1 virtual antennas, to map output symbols for the second receiver to the M2 virtual antennas, to provide the mapped output symbols for the first receiver for transmission on a first frequency subcarrier of T transmit antennas, and to provide the mapped output symbols for the second receiver for transmission on a second frequency subcarrier of the T transmit antennas, wherein M1 and M2 are each equal to one or greater, V is equal to or greater than the larger of M1 and M2, and T is equal to or greater than V; and

a memory coupled to the at least one processor.

29. The apparatus of claim 28, wherein the at least one processor is configured to apply T different cyclic delays for the T transmit antennas.

30. The apparatus of claim 28, wherein M1 is not equal to M2.

31. The apparatus of claim 28, wherein the first and second frequency subcarriers are one frequency subcarrier, and wherein transmissions are sent to the first and second receivers using spatial division multiple access (SDMA).

32. The apparatus of claim 28, wherein the at least one processor is configured to transmit a pilot on each virtual antenna used for transmission.

33. The apparatus of claim 28, wherein the at least one processor is configured to generate transmission symbols for the T transmit antennas based on the mapped output symbols and using orthogonal frequency division multiplexing (OFDM) or single-carrier frequency division multiple access (SC-FDMA) modulation technique.

Means-Plus Claims

34. An apparatus comprising:

means for selecting M1 virtual antennas to use for transmission to a first receiver from among V virtual antennas, wherein M1 is equal to one or greater and V is equal to or greater than M1;

means for selecting M2 virtual antennas to use for transmission to a second receiver from among the V virtual antennas, wherein M2 is equal to one or greater and is also less than or equal to V;

means for mapping output symbols for the first receiver to the M1 virtual antennas;

means for mapping output symbols for the second receiver to the M2 virtual antennas;

means for providing the mapped output symbols for the first receiver for transmission on a first frequency subcarrier of T transmit antennas, wherein T is equal to or greater than V; and

means for providing the mapped output symbols for the second receiver for transmission on a second frequency subcarrier of the T transmit antennas.

35. The apparatus of claim 34, further comprising:

means for applying T different cyclic delays for the T transmit antennas.

36. An apparatus comprising:

at least one processor configured to map output symbols to a plurality of antennas based upon at least one mapping pattern selected from among a plurality of mapping patterns, wherein each mapping pattern indicates a specific mapping of an output symbol to the plurality of antennas; and

a memory coupled to the at least one processor.

37. The apparatus of claim 36, wherein the at least one processor is configured to select different mapping patterns for different frequency subcarriers in a symbol period.

38. The apparatus of claim 36, wherein the at least one processor is configured to select different mapping patterns for symbol periods.

39. The apparatus of claim 36, wherein the at least one processor is configured to select different mapping patterns from among the plurality of mapping patterns for different frequency subcarriers or different symbol periods based on a predetermined pattern.

40. The apparatus of claim 36, wherein the at least one processor is configured to apply a different column of an orthonormal matrix for each of a plurality of frequency subcarriers in accordance with a predetermined pattern, wherein the orthonormal matrix includes a plurality of columns for the plurality of mapping patterns.

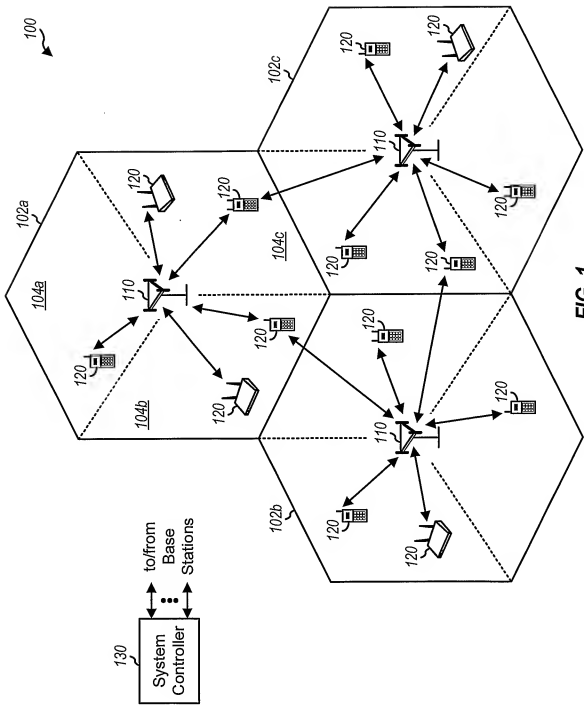
100
102a
102b
102c
104a
104b
104c
110
120
130
System Controller
to/from Base Stations

FIG. 1

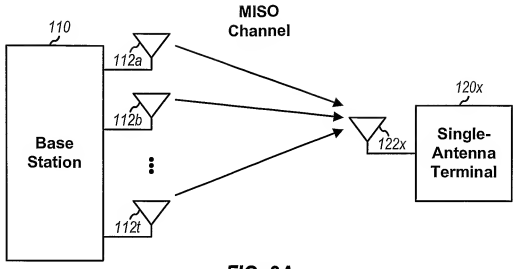
MISO
Channel
110
112a
112b
112t
Base
Station
120x
122x
Single-
Antenna
Terminal

FIG. 2A

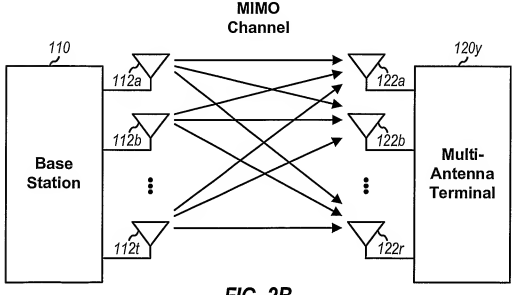
MIMO
Channel
110
112a
112b
112t
Base
Station
120y
122a
122b
122r
Multi-
Antenna
Terminal

FIG. 2B

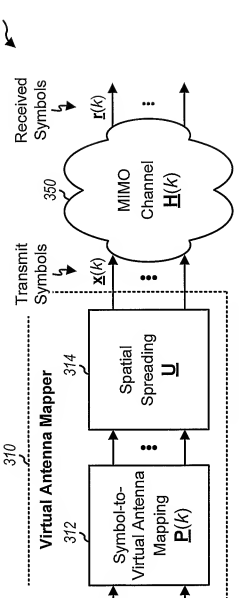
300
Output Symbols
s(k)
310
Virtual Antenna Mapper
312
Symbol-to-Virtual Antenna Mapping P(k)
314
Spatial Spreading U
Transmit Symbols
x(k)
350
MIMO Channel H(k)
Received Symbols
r(k)
Actual MIMO Channel H(k)
Effective MIMO Channel Heff(k)
Used MIMO Channel Hused(k)

FIG. 3

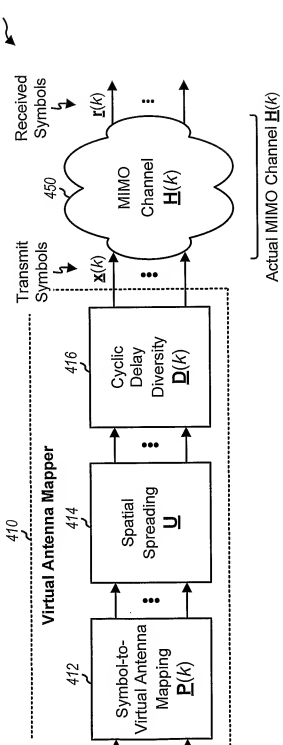
400
Output Symbols
s(k)
Virtual Antenna Mapper
410
412
Symbol-to-Virtual Antenna Mapping P(k)
414
Spatial Spreading U
416
Cyclic Delay Diversity D(k)
Transmit Symbols
x(k)
450
MIMO Channel H(k)
Received Symbols
r(k)
Actual MIMO Channel H(k)
Effective MIMO Channel H_eff(k)
Used MIMO Channel H_used(k)

FIG. 4

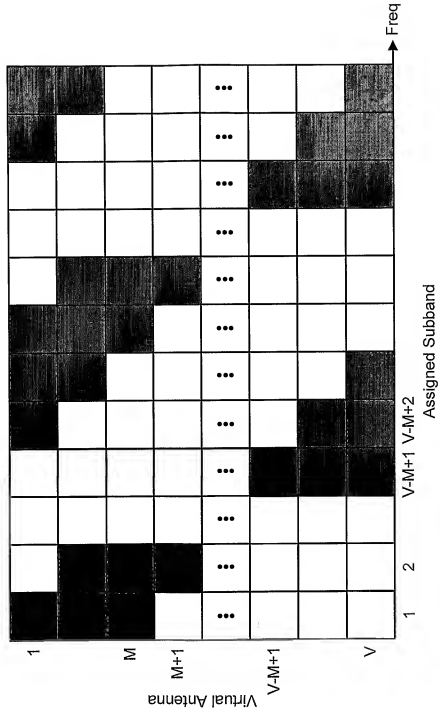
500
Freq
Virtual Antenna
1
M
M+1
V-M+1
V
1
2
V-M+1
V-M+2
Assigned Subband

FIG. 5

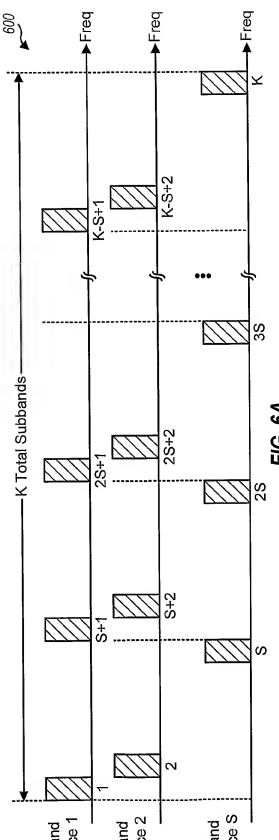
600
K Total Subbands
Subband Interlace 1
Subband Interlace 2
Subband Interlace S
Freq
1
S+1
2S+1
K-S+1
2
S+2
2S+2
K-S+2
S
2S
3S
K

FIG. 6A

610
K Total Subbands
Subband Block 1
Subband Block 2
Subband Block S
Freq
1
N
N+1
2N
K-S+1
K

FIG. 6B

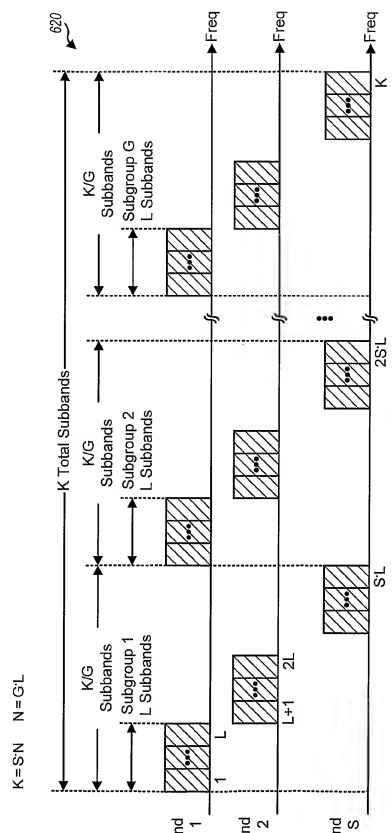
620
K = S'N
N = G'L
K Total Subbands
K/G Subbands
Subgroup 1 L Subbands
K/G Subbands
Subgroup 2 L Subbands
K/G Subbands
Subgroup G L Subbands
Freq
Subband Group 1
Subband Group 2
Subband Group S
1
L
L+1
2L
S'L
2S'L
K

FIG. 6C

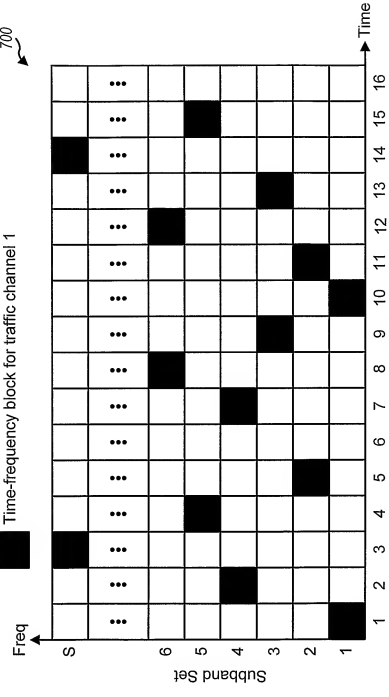
700
Time-frequency block for traffic channel 1
Freq
Time
Subband Set
S
6
5
4
3
2
1
Time Slot
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

FIG. 7

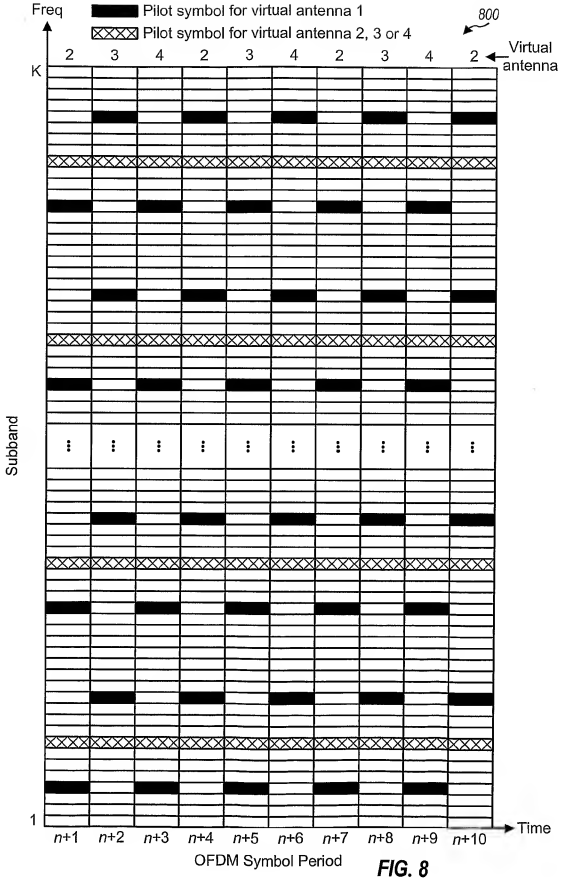
Freq
Pilot symbol for virtual antenna 1
Pilot symbol for virtual antenna 2, 3 or 4
800
2 3 4 2 3 4 2 3 4 2
Virtual antenna
K
Subband
1
Time
n+1 n+2 n+3 n+4 n+5 n+6 n+7 n+8 n+9 n+10
OFDM Symbol Period

FIG. 8

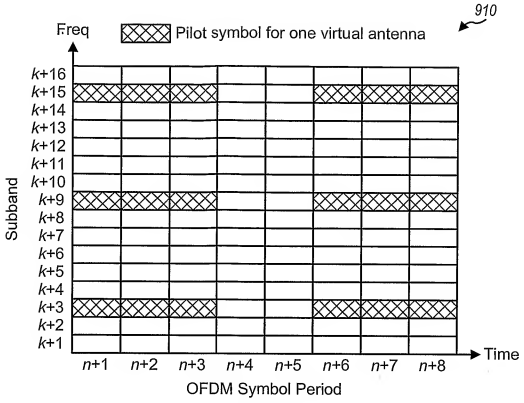
910
Freq
Pilot symbol for one virtual antenna
k+16
k+15
k+14
k+13
k+12
k+11
k+10
k+9
k+8
k+7
k+6
k+5
k+4
k+3
k+2
k+1
Subband
n+1
n+2
n+3
n+4
n+5
n+6
n+7
n+8
Time
OFDM Symbol Period

FIG. 9A

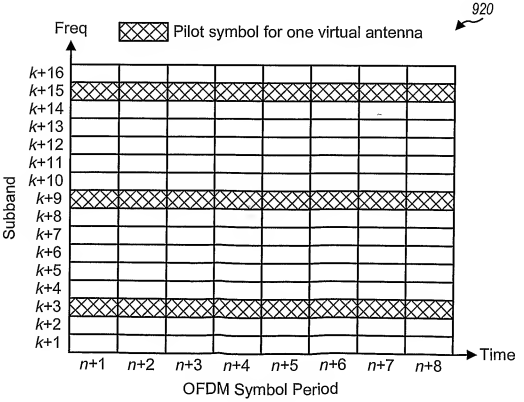
920
Freq
Pilot symbol for one virtual antenna
k+16
k+15
k+14
k+13
k+12
k+11
k+10
k+9
k+8
k+7
k+6
k+5
k+4
k+3
k+2
k+1
Subband
n+1
n+2
n+3
n+4
n+5
n+6
n+7
n+8
Time
OFDM Symbol Period

FIG. 9B

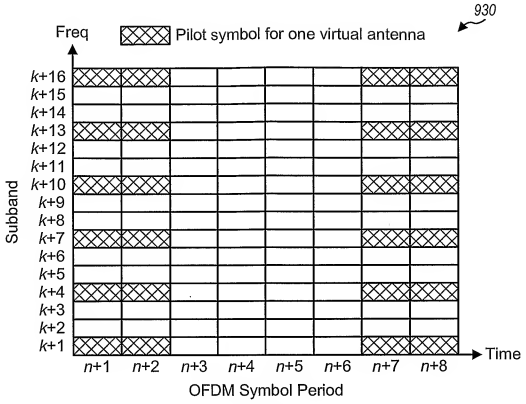
930
Freq
Pilot symbol for one virtual antenna
Subband
k+16
k+15
k+14
k+13
k+12
k+11
k+10
k+9
k+8
k+7
k+6
k+5
k+4
k+3
k+2
k+1
Time
n+1
n+2
n+3
n+4
n+5
n+6
n+7
n+8
OFDM Symbol Period

FIG. 9C

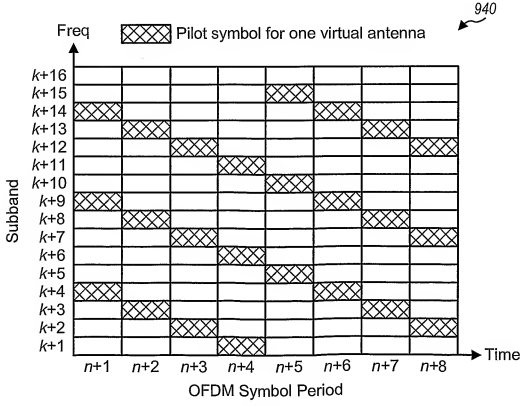
940
Freq
Pilot symbol for one virtual antenna
Subband
k+16
k+15
k+14
k+13
k+12
k+11
k+10
k+9
k+8
k+7
k+6
k+5
k+4
k+3
k+2
k+1
Time
n+1
n+2
n+3
n+4
n+5
n+6
n+7
n+8
OFDM Symbol Period

FIG. 9D

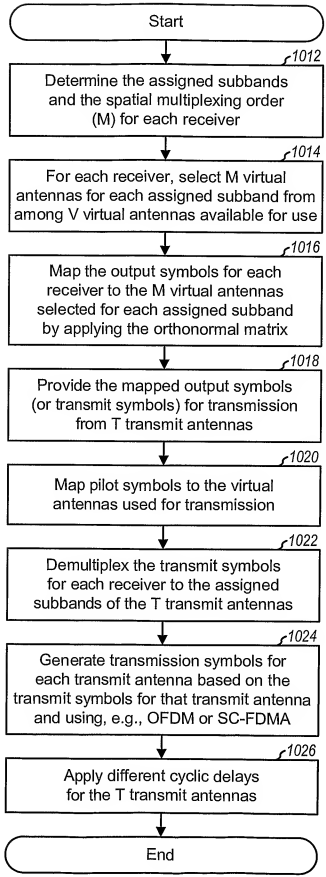
Start
1000
1012
Determine the assigned subbands and the spatial multiplexing order (M) for each receiver
1014
For each receiver, select M virtual antennas for each assigned subband from among V virtual antennas available for use
1016
Map the output symbols for each receiver to the M virtual antennas selected for each assigned subband by applying the orthonormal matrix
1018
Provide the mapped output symbols (or transmit symbols) for transmission from T transmit antennas
1020
Map pilot symbols to the virtual antennas used for transmission
1022
Demultiplex the transmit symbols for each receiver to the assigned subbands of the T transmit antennas
1024
Generate transmission symbols for each transmit antenna based on the transmit symbols for that transmit antenna and using, e.g., OFDM or SC-FDMA
1026
Apply different cyclic delays for the T transmit antennas
End

FIG. 10

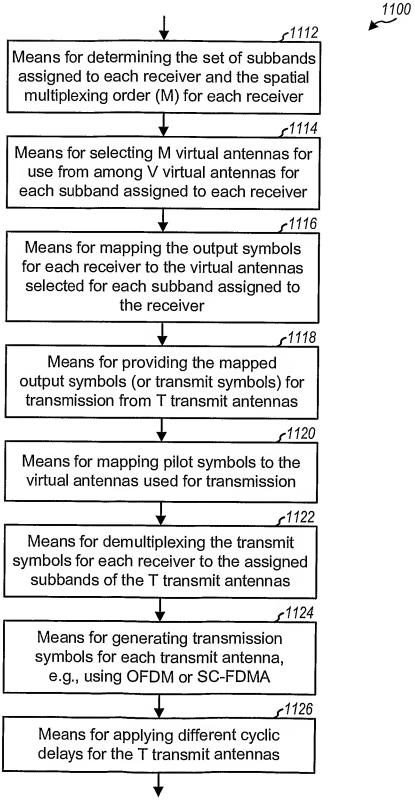
1100
1112
Means for determining the set of subbands assigned to each receiver and the spatial multiplexing order (M) for each receiver
1114
Means for selecting M virtual antennas for use from among V virtual antennas for each subband assigned to each receiver
1116
Means for mapping the output symbols for each receiver to the virtual antennas selected for each subband assigned to the receiver
1118
Means for providing the mapped output symbols (or transmit symbols) for transmission from T transmit antennas
1120
Means for mapping pilot symbols to the virtual antennas used for transmission
1122
Means for demultiplexing the transmit symbols for each receiver to the assigned subbands of the T transmit antennas
1124
Means for generating transmission symbols for each transmit antenna, e.g., using OFDM or SC-FDMA
1126
Means for applying different cyclic delays for the T transmit antennas

FIG. 11

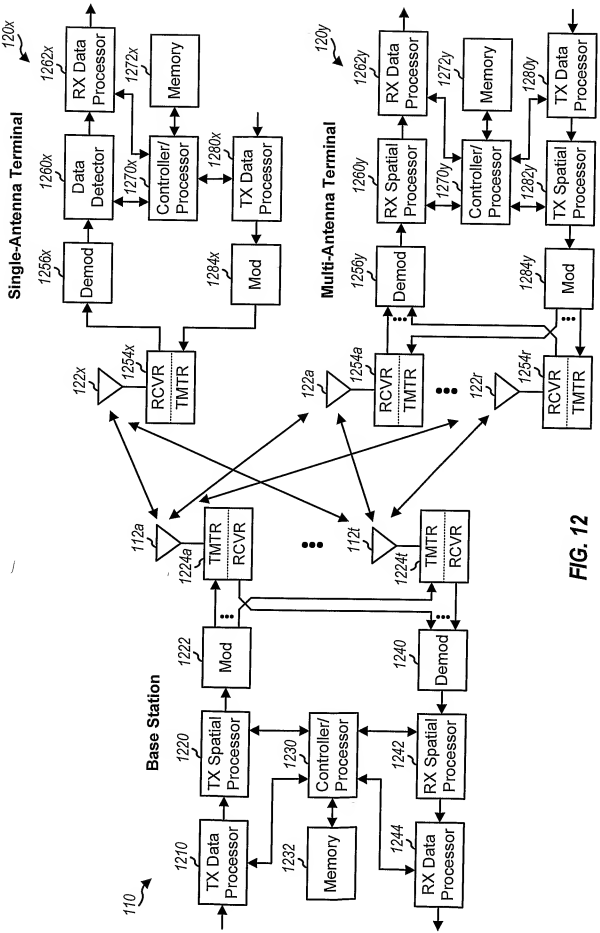
110
Base Station
1210
TX Data Processor
1220
TX Spatial Processor
1222
Mod
1224a
TMTR
RCVR
112a
1232
Memory
1230
Controller/ Processor
1240
Demod
1242
RX Spatial Processor
1244
RX Data Processor
Single-Antenna Terminal
120x
122x
1254x
RCVR
TMTR
1256x
Demod
1260x
Data Detector
1270x
Controller/ Processor
1262x
RX Data Processor
1272x
Memory
1280x
TX Data Processor
1284x
Mod
Multi-Antenna Terminal
120y
122a
122r
1254a
1254r
1256y
Demod
1260y
RX Spatial Processor
1270y
Controller/ Processor
1262y
RX Data Processor
1272y
Memory
1280y
TX Data Processor
1282y
TX Spatial Processor
1284y
Mod

FIG. 12